SEPIA — A New Instrument for the Atacama Pathfinder Experiment (APEX) Telescope

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The Swedish-ESO PI receiver for APEX (SEPIA) was installed at the APEX telescope in 2015. This instrument currently contains ALMA Band 5 (157–212 GHz) and Band 9 (600–722 GHz) receivers. Commissioning and science verification for Band 5 have been successfully completed but are still ongoing for Band 9. The SEPIA instrument is briefly described and the commissioning of the Band 5 receiver and results from the first science observations are presented.

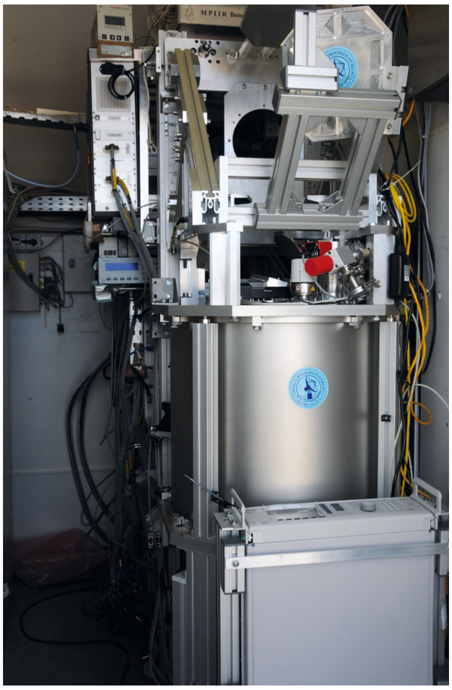
In 2015, the Atacama Pathfinder Experiment (APEX) telescope received a new instrument, the Swedish-ESO PI receiver for APEX. The arrival of SEPIA at APEX featured in several press releases[1,2]. More information about the instrument can be found on the APEX webpage[3]. Currently, Band 5 receivers are also being installed at antennas of the Atacama Large Millimeter/submillimeter Array (ALMA) and it is planned to offer this band for science proposals in Cycle 5 (beginning September 2017). Preparatory observations with SEPIA Band 5 at APEX to pave the way for future ALMA projects are thus possible now. ESO will organise a dedicated workshop on SEPIA and the preparatory work for ALMA Band 5 at the beginning of 2017.

Description of SEPIA

SEPIA is a single pixel heterodyne instrument that can accommodate three ALMA-like receiver cartridges. It currently contains ALMA Band 5 (157.36–211.64 GHz) and Band 9 (600–722 GHz) receivers. A Band 7 receiver (275–373 GHz) is planned to be added in early 2018. The SEPIA receiver project was realised within one year: the decision for a new instrument for APEX was taken in February–March 2014 and the installation at the telescope was performed in February 2015. Details of the instrument and its commissioning will be presented in Belitsky et al. (in prep.).

The tertiary optics to illuminate the SEPIA cartridges inside the Nasmyth cabin A of the APEX telescope were designed, constructed, and installed by the Group for Advanced Receiver Development (GARD) at Onsala Space Observatory (OSO) in Sweden. The SEPIA cryostat was also manufactured by GARD. It provides the required mechanical, cryogenic, vacuum, optical and electrical interfaces for the receiver cartridges. The control system and software were also developed by GARD at OSO. The total weight of the SEPIA instrument (including the tertiary optics and its supporting frame, the integrated turbo-pump and three cartridges) is ~ 315 kg. Figure 1 shows a picture of the installed SEPIA instrument.

An ALMA Band 5 pre-production cartridge (Billade et al., 2012) was refurbished by GARD with full-production mixer components as well as a local oscillator (LO) system and a warm cartridge assembly, which were purchased from the National Radio Astronomy Observatory (NRAO). Band 5 is a dual-polarisation sideband-separated (2SB) receiver which covers the frequency range 157.36–211.64 GHz. Each sideband has a total bandwidth of 4 GHz. The central frequencies of the two sidebands are separated by 12 GHz, corresponding to an intermediate frequency (IF) of 4–8 GHz. At 183 GHz, the beam size is 34 arcseconds. The single-sideband noise temperature is below 55 K at all frequencies of the band. The sideband rejection ratio is > 10 dB at all frequencies and 18.5 dB on average.



E. Sundin/OSO

Figure 1. The SEPIA instrument installed at APEX.

During Band 5 and Band 9 observations, the SEPIA receiver is connected to the Max-Planck-Institut für Radioastronomie's eXtended bandwidth Fast Fourier Transform Spectrometer (XFFTS; Klein et al., 2012). Each sideband is recorded by two 2.5 GHz wide XFFTS units, with an overlap of 1 GHz. The back end provides a fixed number of 65 536 and 32 768 channels per sub-band of the lower and upper sideband, which yields spectral resolutions of 38 kHz and 76 kHz, respectively. The main transition of astronomical interest in the frequency range of this receiver is the H_2O(3–2) line at 183.3 GHz. Table 1 lists the astrophysically important molecules and their transitions within Band 5.

The atmospheric transmission at APEX at the frequency of the 183 GHz line is better than 0.3 for a precipitable water vapour (PWV) of < 0.5 mm, which happens for about 50 days per year (15 % of the total observing time). At frequencies outside of the atmospheric water line (≲ 175 GHz, ≳ 192 GHz), the atmosphere is much more transparent and observations can be conducted for most of the year. Figure 2 shows the atmospheric transmission for the whole band for five different PWV values. In addition, the frequencies of the brightest transitions of various molecules (listed in Table 1) in the band are indicated.

The Band 9 cartridge was built by the Netherlands Research School for Astronomy (NOVA) instrumentation group, following the specifications of the ALMA Band 9 receivers (Baryshev et al., 2015). Band 9 is a dual-polarisation double sideband (DSB) receiver covering the frequency range 600–722 GHz, again recorded over an IF of 4–8 GHz. At 660 GHz, the beam width is 9.5 arcseconds. The DSB noise temperature is 70–125 K. Similarly to Band 5, Band 9 is connected to the XFFTS backend. It is planned to upgrade the Band 9 DSB receiver with a 2SB receiver in February/March 2017. First science verification observations have already been conducted and, as an example, Figure 3 shows the H_2O spectrum of the supergiant star AH Sco at 658 GHz (Baudry et al., in prep.).

Commissioning

The SEPIA Band 5 receiver was installed and successfully commissioned between February and September 2015. The technical commissioning of the Band 9 receiver was performed between February and March 2016 by a joint team from GARD and NOVA. Sky commissioning of Band 9 is still ongoing.

Technical commissioning

During the technical commissioning of both SEPIA receivers, the hardware (reference LO, phase lock loop [PLL] synthesiser, IF switches, vacuum control gauge, turbo-pump, computerised control system, etc.) was installed at the telescope. The tertiary optics were aligned in the cabin and the SEPIA cryostat and the cold

Molecule	Transition	Frequency (GHz)	Comment
H_2O	$J_{Ka,Kc} = 3_{1,3}–2_{2,0}$	183.31	
$H_2{}^{18}O$	$J_{Ka,Kc} = 3_{1,3}–2_{2,0}$	203.41	
HCN	J = 2–1	177.26	
$H^{13}CN$	J = 2–1	172.68	
$HC^{15}N$	J = 2–1	172.11	
HNC	J = 2–1	181.32	
HCO^+	J = 2–1	178.38	
$H^{13}CO^+$	J = 2–1	173.51	
$HC^{18}O^+$	J = 2–1	170.32	
CS	J = 4–3	195.95	
^{13}CS	J = 4–3	184.98	
$C^{34}S$	J = 4–3	192.82	
N_2H^+	J = 2–1	186.34	
CH_3CN	J = 9–8	165.60	Several K-components
	J = 10–9	183.90	Several K-components
	J = 11–10	202.30	Several K-components
CH_3CCH	J = 10–9	170.90	Several K-components
	J = 11–10	187.90	Several K-components
	J = 12–11	205.00	Several K-components
CH_3OH	J = 4–3	193.50	Several lines
CCH	N = 2–1	174.70	Several lines
SiO, v = 0	J = 4–3	173.69	
SiO, v = 1	J = 4–3	172.48	
SiO, v = 2	J = 4–3	171.28	
H_2S	$J_{Ka,Kc} = 1_{1,1}–1_{0,1}$	168.76	

Table 1. Astrophysically important molecular transitions in SEPIA Band 5.

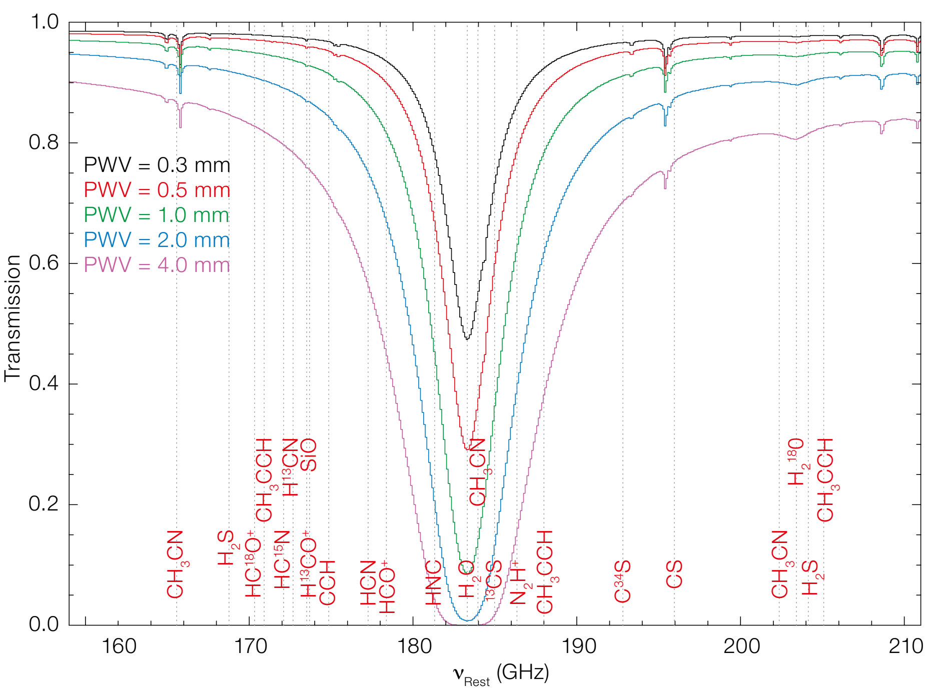


Figure 2. Atmospheric transmission in Band 5 for five different water vapour levels: PWV = 0.3 mm (black), PWV = 0.5 mm (red), PWV = 1.0 mm (green), PWV = 2.0 mm (blue), PWV = 4.0 mm (pink). The transitions of Table 1 are marked.

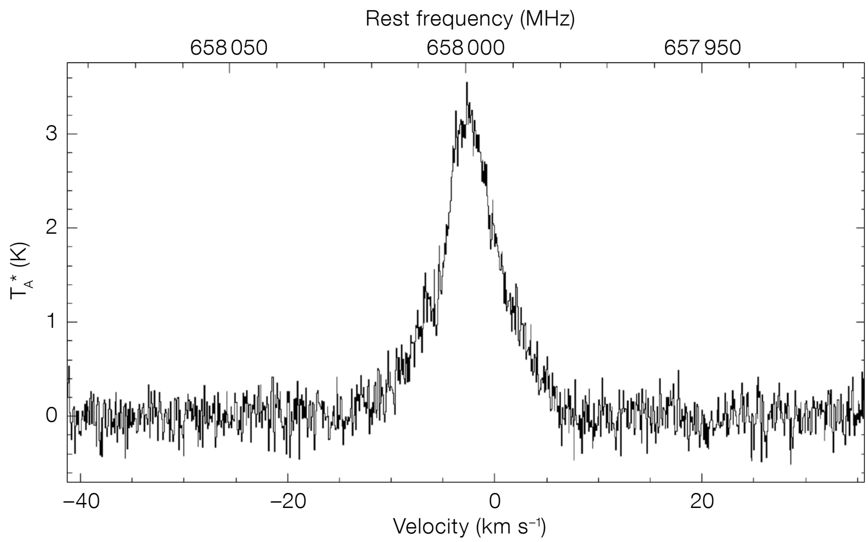


Figure 3. SEPIA Band 9 H_2O spectrum of AH Sco at 658 GHz (Baudry et al., in prep.).

head compressor installed. The integrity of the whole system was tested and the alignment of the optics was verified with small nitrogen-cooled absorbers.

Sky commissioning

A number of on-sky tests have to be conducted before a new instrument can be offered for observing time. By tuning Band 5 every 0.5 GHz, we confirmed that the whole tuning range from 157.36–211.64 GHz is accessible. Observing strong water masers as part of the Science Verification, Humphreys et al. (in prep), determined the sideband suppression level to be 17.7 dB by comparing the water line in the upper sideband to its ghost line in the lower sideband. From a preliminary analysis of planet observations (for Jupiter, Uranus and Mars), we determined an average main beam efficiency η_{mb} = 0.68 at 208 GHz, corresponding to a Jy/K conversion factor of 38. A more detailed analysis, examining the frequency dependence over the entire band, will be published in Belitsky et al. (in prep), and the resulting values will be given on the APEX webpage[3].

Pointing and focus observations at APEX are conducted towards compact sources with either strong continuum or line emission. For the other APEX heterodyne instruments, these observations are often done in the main transitions of the CO molecule. Since the Band 5 frequency range does not contain a CO transition (Table 1), we had to find sources that emit strongly in other molecular transitions. We chose evolved stars that are bright in HCN or SiO. After testing their quality as pointing sources, we constructed a pointing catalogue which covers the whole local sidereal time (LST) range. The positions of the sources are plotted in Figure 4. The pointing sources are being used to compile a good pointing model for Band 5 (more details will be provided in Belitsky et al., in prep.). With this receiver, pointing accuracies of 2.5 arcseonds are achieved.

Recalibration of Band 5 data

The online calibration of spectral line observations at the APEX telescope is based on SKY-HOT-COLD calibration scans immediately before the spectral line data are taken. During these scans, observations of blank sky, a hot load at ambient temperature and a cold load at liquid nitrogen temperature are conducted. From the HOT and COLD signal, the online calibrator determines the receiver temperature. From the SKY phase, it calculates the sky temperature, correcting for spillover and forward efficiency. Based on the elevation of the SKY observations and a sophisticated atmospheric model (ATM: Pardo et al., 2001), the opacity in image and signal band is determined.

In the online calibration, only one opacity value is calculated for the whole 2.5 GHz sub-band. This is sufficient if the atmospheric opacity is reasonably flat. However, in Band 5, due to the water absorption of the atmosphere, this approach

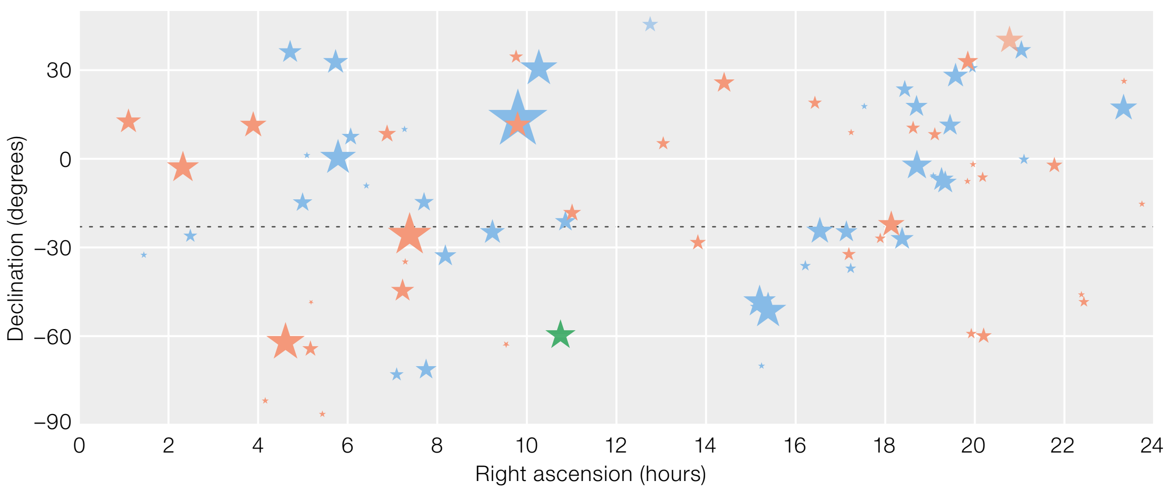


Figure 4. Local Siderial Time (LST) distribution of Band 5 pointing sources (HCN [blue], SiO [red] and continuum [green]). The size of each symbol is proportional to the logarithm of the integrated flux (K km s−1). The dotted line indicates the latitude of the APEX telescope.

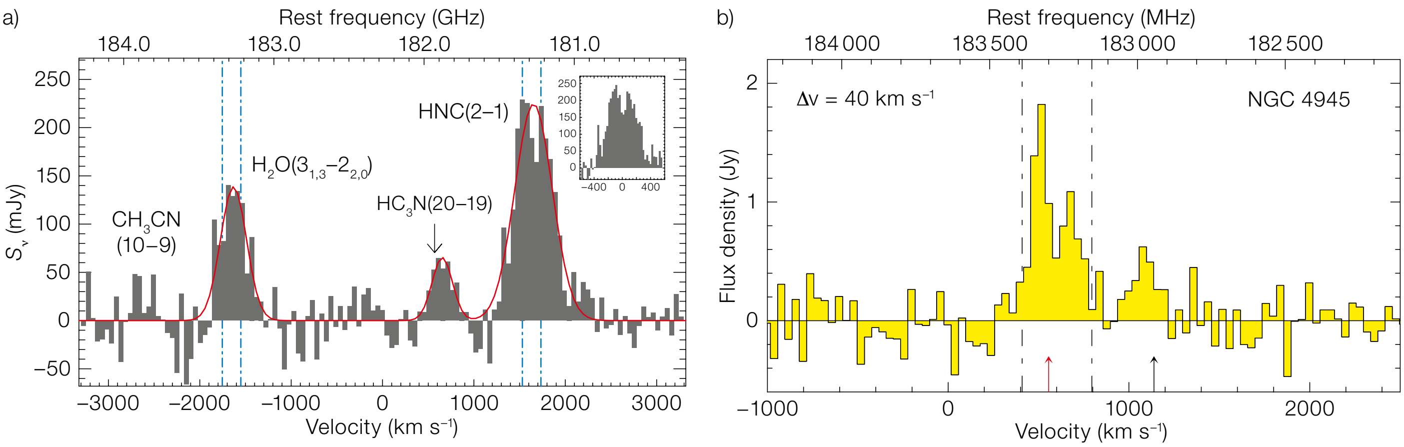


Figure 5. (a) 183 GHz H_2O emission detected towards Arp 220 (from Galametz et al. 2016). Other molecular lines are detected, such as HNC and HC_3N which trace the dense gas. The inset shows HNC double-peak profile at a 25 km s^{-1} resolution. (b) 183 GHz water maser emission from the nearby galaxy NGC 4945 (from Humphreys et al., 2016). The data were binned to 40 km s^{-1} resolution. The red arrow indicates the approximate galactic systemic velocity of 556 km s^{-1}.

is insufficient for observations close to 183.3 GHz. This type of data needs to be recalibrated offline at the telescope. In the offline calibration, opacity values are determined in chunks of 128 channels (the resolution of the atmospheric model). The online calibrated data underestimate the emission around 183 GHz by up to 30 %. The goal is to upgrade the online calibration for SEPIA Band 5 (and later Band 9) observations to provide such optimally calibrated data.

Science with SEPIA Band 5

Nine ESO[4] and five OSO[5] projects were submitted and observed for science verification of Band 5. The instrument has been offered for regular projects since ESO and OSO Period 96. Twenty-nine ESO proposals and 25 OSO proposals (including two Director's Discretionary Time proposals in Period 95) have been accepted until now. For ESO, these proposals represent a third of all APEX proposals during Periods 96–98. Since the installation of Band 5, the instrument has been used for almost 1000 hours.

Many different molecules have transitions in the SEPIA Band 5 frequency range (Table 1). One of the main science drivers for an ALMA Band 5 receiver at APEX was the possibility of observing the 183.3 GHz water line. Interstellar water emission was first detected by Cheung et al. (1969) and since then the Herschel Space Observatory has shown that gaseous water is widespread in molecular clouds in our Galaxy (van Dishoeck et al., 2011). With APEX, surveys for both maser and thermal water emission towards a large number of sources are feasible.

The water molecule is an important tracer of the energetic processes which take place during the formation of low- and high-mass stars. In combination with the lower optical depth $H_2{}^{18}O$ transition at 203.4 GHz, the observations probe the water content even in the inner parts of hot molecular cores, complementing space-based water observations (for example, from Herschel). The 183.3 GHz line has also been detected in the O-rich circumstellar envelopes of several evolved stars with mass-loss rates exceeding 10^{-6} $M_\odot$/yr (González-Alfonso et al., 1998, 1999). Observations of this transition with APEX will thus allow the study of the water abundance in evolved stars. In addition, the degree of the linear polarisation of the 183.3 GHz water maser emission can be determined from dual-polarisation observations with Band 5 (Humphreys et al., in prep.).

Beyond the Galaxy, water maser observations will provide information about the water content of nearby (z < 0.1) galaxies, as well as the high temperature and density regions of active galactic nuclei (AGN). In the Seyfert 2 galaxy NGC 4945, 183.3 GHz H_2O megamaser emission was detected for the first time with SEPIA Band 5 (Humphreys et al. 2016; see Figure 5b); the strongest extragalactic submillimetre water maser detected to date. The emission seems to be dominated by that from the AGN central engine.

Galametz et al. (2016) (Figure 5a) recently detected water (183.3 GHz) and the methanol (4–3) group (193.5 GHz) in the ultra-luminous infrared galaxy Arp 220. No time variations were observed in the megamaser water line compared to previous observations, supporting arguments against an AGN nuclear origin for the line.

The J = 2–1 transitions of the nitrogen-bearing species HCN, HNC, and N_2H^+, as well as HCO^+, are available in the SEPIA Band 5 frequency range. Their isotopologues $H^{13}CN$, $HC^{15}N$, $H^{13}CO^+$, and $HC^{18}O^+$ are observable in one frequency setting, as are HCN and HCO^+. These transitions serve as low-energy complements to the higher J-lines which are covered by other APEX bands, probing colder/lower density material. In evolved stars, simultaneous observations of HCN and SiO allow the determination of the HCN/SiO intensity ratio which is indicative of the star's chemical type (Olofsson et al., 1998).

The symmetric top molecules CH_3CN and CH_3CCH have several K-ladders in the band. Also, the methanol J = 4–3 line forest around 193.5 GHz, and the set of lines of CCH(2–1) around 174.7 GHz, are accessible with SEPIA Band 5. All these transitions are excellent temperature tracers of the denser molecular gas. They are more

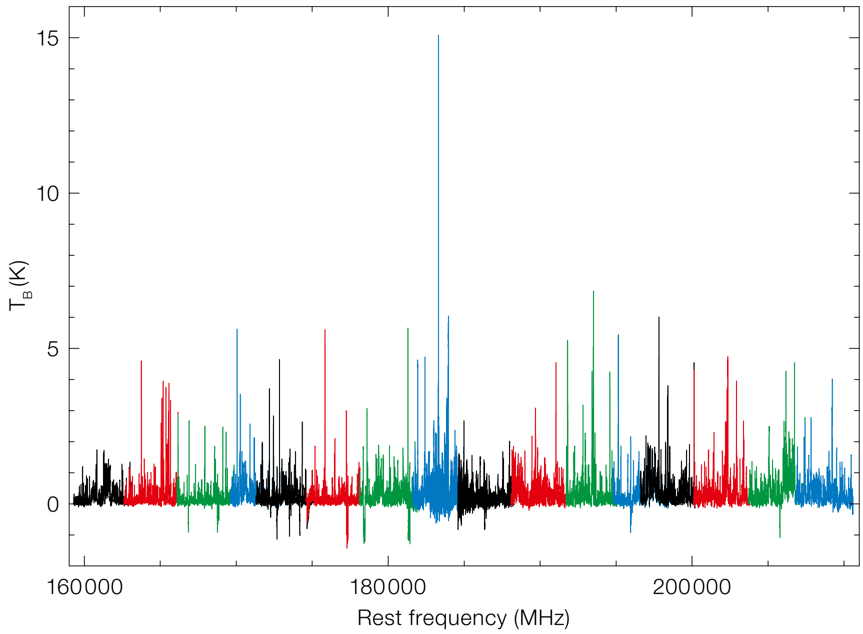


Figure 6. Spectral line survey of Sgr B2. The eight different frequency tunings are marked in black, red, green, and blue. The strongest emission line is the H_2O transition at 183.3 GHz. Absorption lines, such as of HCN, HNC, and HCO^+, are also detected. From Immer et al. in prep.

sensitive to lower temperatures than the corresponding transitions in other APEX bands. Molinari et al. (2016) observed CH_3CCH(12–11) towards 51 dense clumps and determined their gas temperatures.

For all sources at $z > 0.615$, at least one CO transition falls within the frequency range of the SEPIA Band 5 receiver. This allows observations of high-J CO transitions in bright submillimetre galaxies in order to investigate their CO spectral line energy distributions or confirm their redshifts. Strandet et al. (2016), who studied the redshift distribution of SPT sources, used the SEPIA CO observations of two sources to confirm their redshifts. In addition to CO, detecting [C II] in highly redshifted sources ($z > 8.9$) is challenging for APEX, but could be extremely rewarding.

Due to the instantaneous bandwidth of 8 GHz, the whole frequency range of SEPIA Band 5 can be covered with only eight frequency tunings with several 100 MHz overlap. An ESO Science Verification project observed the frequency range 159.2–210.7 GHz towards the high-mass star forming complex Sgr B2 (Figure 6), proving once again the line-richness of this source and illustrating the large number of transitions that can be detected in SEPIA Band 5 (Immer et al., in prep.).

Acknowledgements

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Links

[1] OSO SEPIA press release: http://www.chalmers.se/en/centres/oso/news/Pages/apex-sepia-alma-band-5-water-space.aspx
[2] ESO SEPIA press release: https://www.eso.org/sci/publications/announcements/sciann15015.html
[3] SEPIA webpage: http://www.apex-telescope.org/instruments/pi/sepia/
[4] ESO Science Verification: http://www.eso.org/sci/activities/apexsv/sepia/sepia-band-5.html
[5] OSO Science Verification: http://www.chalmers.se/en/centres/oso/Documents/APEX%20Observed%20projects/APEX-SepiaScienceVerification_Apr-Jul-2015_P95.pdf

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Long exposure photograph of the APEX telescope during night-time observing.